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Experimental demonstration and performance estimation of a new relaxation oscillator using a superconducting Schmitt trigger inverter

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Abstract

An experimental demonstration and performance estimation of a superconducting relaxation oscillator using the Schmitt trigger inverter are reported. The superconducting Schmitt trigger inverter is composed of a threshold gate that uses coupled superconducting quantum interference devices. The oscillator is based on the general concept of using the Schmitt trigger inverter and a delayed feedback loop. The oscillation frequency is characterized by the circuit parameters of the delayed feedback loop and the hysteresis structure of the Schmitt trigger. The circuit parameter dependence of the oscillation frequency is estimated by numerical simulations. In order to confirm the circuit operation, the proposed relaxation oscillator is fabricated by a Nb/AlOx/Nb standard process and tested. The operation of the oscillator is demonstrated successfully.

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Keywords: superconductivity; superconducting quantum interference device (SQUID); relaxation oscillator; Schmitt trigger

1. Introduction

Recently, we have proposed a new superconducting relaxation oscillator based on the Schmitt trigger inverter using superconducting quantum interference device (SQUID) gates [1]. The Schmitt trigger inverter consists of a threshold gate with hysteretic characteristics using two coupled SQUIDs (c-SQUIDs) gates with a cascade connection [2]. Although, several other superconducting relaxation oscillators have already been proposed, these are

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based on the hysteresis properties of the switching characteristics of one or two Josephson junctions shunted by a series of inductance and resistance [3]-[6]. On the other hand, it is expected that our new relaxation oscillator has high current drivability because it does not use the hysteretic structure on the *I–V* curve of the Josephson junction. Such an oscillator has valuable use as a clock generator in superconducting logic circuits or sensor devices operating in the low temperature environment. In this paper, an experimental demonstration and a performance estimation of the new oscillator are reported. The oscillation frequency is characterized by the circuit parameters of the delayed feedback loop and the hysteresis structure of the Schmitt trigger. The circuit parameter dependence of the oscillation frequency is estimated by numerical simulations. The proposed relaxation oscillator is fabricated by the AIST standard process (STP2) [7] and further tested. The operation of the fabricated relaxation oscillator is experimentally demonstrated.

2. Relaxation oscillator using superconducting Schmitt Trigger Inverter

2.1. Schmitt Trigger Inverter Using Coupled SQUIDs Gates with Flat Output Characteristics

Figure 1(a) shows the circuit diagram of the Schmitt trigger inverter that is composed of cascaded two-stage c-SQUIDs gates. The double-junction SQUID (DC-SQUID) reads out the quantum state of the single-junction SQUID. Because the transition of the quantum state of the single-junction SQUID follows a step-like function, the output voltage of the DC-SQUID is characterized by a sharp rise in the voltage. The second stage C-SQUIDs gate operates as the output buffer gate for generating step-like output characteristics [2].

To obtain the characteristics with a Schmitt trigger shape, the input gate must have hysteretic characteristics. Such characteristics can be obtained by solely increasing LI_c product of the single-junction SQUID. In addition, a negative offset bias current I_{off1} is supplied to the first stage c-SQUID gate in order to achieve an inverting configuration [1]. Figure 1(b) shows the static input vs. output characteristics of the Schmitt trigger inverter. The output V_{out2} shows characteristics identical to the Schmitt trigger inverter.

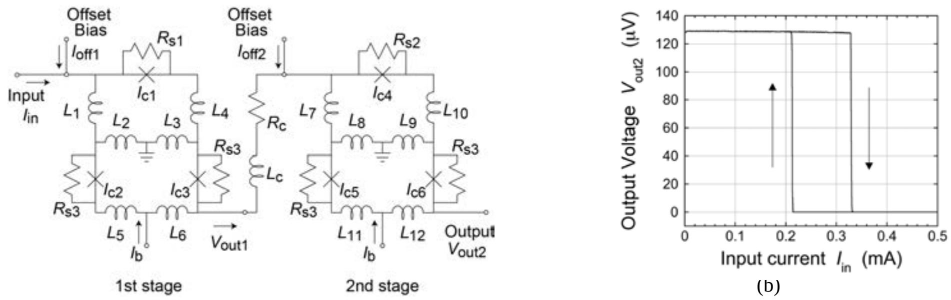
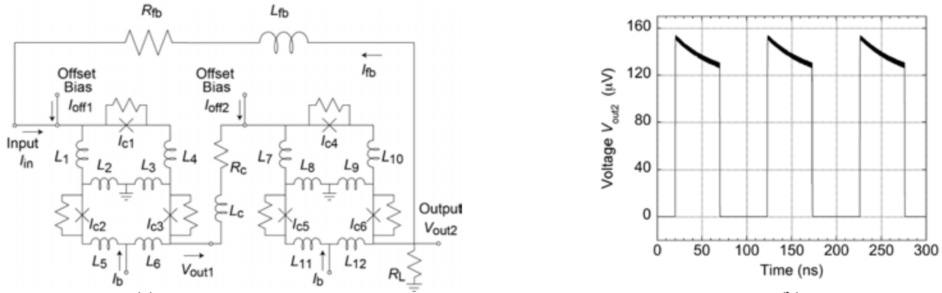


Fig. 1. (a) Threshold gate composed of cascaded two-stage c-SQUIDs gates. The device parameters used in the design are I_{c1} = 0.205 mA, $I_{c2} = I_{c3} = I_{c5} = I_{c6}$ = 0.750 mA, I_{c4} = 0.193 mA, L_1 = 1.32 pH, $L_2 = L_3 = L_8 = L_9$ = 1.13 pH, $L_4 = L_{10}$ = 0.40 pH, $L_5 = L_6 = L_{11} = L_{12}$ = 0.34 pH, L_7 = 1.20 pH, L_c = 5.0 pH, R_c = 0.10 Ω, I_b = 1.45 mA, R_{s1} = 1.9 Ω, R_{s2} = 2.0 Ω, and R_{s3} = 0.52 Ω. (b) Simulated static input vs. output characteristics of the Schmitt trigger inverter. (I_{off1} = -0.80 mA, I_{off2} = 0.35 mA, and output load R_{load} = 0.5 Ω)

2.2. Relaxation Oscillator Using Schmitt Trigger Inverter

It is well known that a circuit composed of the Schmitt trigger and some negative feedback element operates as a simple relaxation oscillator. Using the semiconductor circuits, this is achieved by connecting a single RC integrating circuit between the output and the input of an inverting Schmitt trigger. On the other hand, a typical delay element in the superconducting electronics is usually obtained by certain combinations of a resistance and an inductance. Figure 2(a) shows a relaxation oscillator using the superconducting Schmitt trigger inverter and a delay element using a series of the resistance R_{fb} and the inductance L_{fb}.

Figure 2(b) shows a simulated output waveform of the relaxation oscillator using the superconducting Schmitt trigger inverter. This output voltage is monitored by using an additional *RC* filter, with R = 1 kΩ and C = 0.1 pF, in order to remove the high frequency spectrum due to Josephson oscillation. This low pass filter does not affect the operation of the relaxation oscillator substantially, because the resistance R is rather large as compared to the load resistance R_L. It is confirmed that periodic pulse signals are generated.



(a) (b)

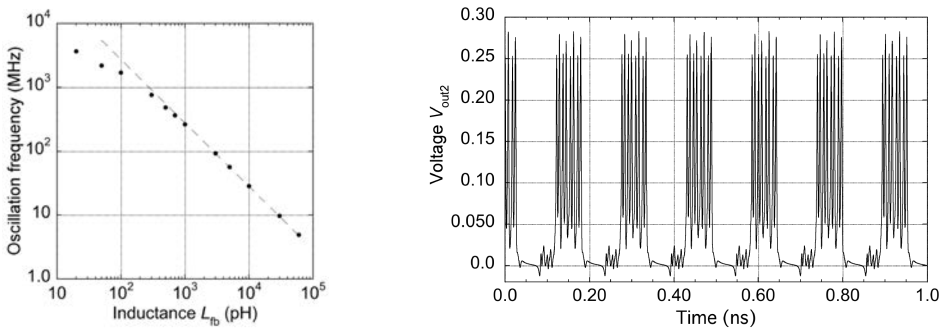
Fig. 2. (a) Relaxation oscillator using the superconducting Schmitt trigger inverter. The device parameters used in the design are L_{fb} = 30.0 nH, R_{fb} = 0.50 Ω, R_L = 1.90 Ω, I_{off1} = -0.665 mA, and I_{off2} = 0.35 mA. Other circuit parameters are the same as those described in Fig. 1. (b) A simulated output waveform of the relaxation oscillator using the superconducting Schmitt trigger inverter. This output voltage was monitored using an RC filter, with R = 1 kΩ and C = 0.1 pF, in order to remove the high frequency spectrum due to Josephson oscillation. The simulation is based on the parameters of a 2.5 kA/cm^2 Nb/AlOx/Nb Josephson junction.

2.3. Circuit Parameter Dependence of the Oscillation Frequency

Using the semiconductor Schmitt trigger circuit, the relaxation oscillator is achieved by connecting a single RC integrating circuit between the inverted output and the input. The oscillation frequency is mainly defined by the RC product; therefore, it can be easily changed by changing the additional integrating circuit. The oscillation frequency of our superconducting oscillator can be similarly changed by changing the parameters of the integrating circuit.

Figure 3(a) shows the dependence of the simulated oscillation frequency on the inductance in the feedback loop. The frequency is inversely proportional to the inductance in the range of up to about 1 GHz. However, the frequencies beyond 1 GHz are not inversely proportional to the inductance, because the value of the time constant L/R becomes close to the value of the gate delay of the Schmitt trigger. The operation of the oscillator with a pulse duty ratio of 0.5 is confirmed up to a frequency of 3.7 GHz as shown in Fig. 3(a). The pulse shape collapses in the range of the frequencies over 3.7GHz. Tuning parameters about the gate delay and the duty ratio are required for a high-speed operation. The pulse duty ratio is mainly adjusted by changing an offset bias current.

Figure 3(b) shows the high-speed operation of a relaxation oscillator using lightly tuned circuit parameters, which are R_c = 0.3 Ω and I_{off1} = -0.645 mA. The operation of the relaxation oscillator at a frequency of 6.5 GHz is confirmed by this result.



(a) (b)

Fig. 3. (a) Dependence of the simulated oscillation frequency on the inductance in the feedback loop. Dashed line is the fitted line, denoting the relationship of inverse proportionality. (b) High-speed operation of a relaxation oscillator using lightly tuned circuit parameters which are R_c = 0.3 Ω and I_{off1} = -0.645 mA.

3. Demonstration of a fabricated relaxation oscillator using superconducting Schmitt trigger inverter

In order to confirm the circuit operation, a relaxation oscillator using the Schmitt trigger inverter was fabricated by using the 2.5kA/cm^2 Nb/AlOx/Nb AIST standard process (STP2). Figure 4(a) shows the design layout of the fabricated oscillator. The circuit parameters are the same as shown in Fig. 2(a). The feedback inductor is designed using a stripline structure of a superconducting wiring layer as shown in Fig. 4(a). Figure 4(b) shows an experimental result of the fabricated circuit. The output signal is amplified using an AC-coupled 50 Ω broadband amplifier with a gain of 21 dB and a frequency response in the range of 80 kHz to 13.5 GHz to measure small voltage pulse signals generated by the c-SQUIDs gate. Although we cannot accurately evaluate the signal amplitude because of inserting the AC-coupled amplifier, the pulse amplitude is measured with an amplification ratio of about ten. The periodic pulse signals are confirmed from this result. The oscillation frequency is estimated to be about 8.1MHz. The measured frequency is lower than the simulation result (9.7MHz) shown in Fig. 2(b). We suppose that this discrepancy is mainly due to the parameter deviation of the feedback inductor. Measurements of circuits with other inductor configurations are required in order to evaluate the parameter dependence of the frequency in detail.

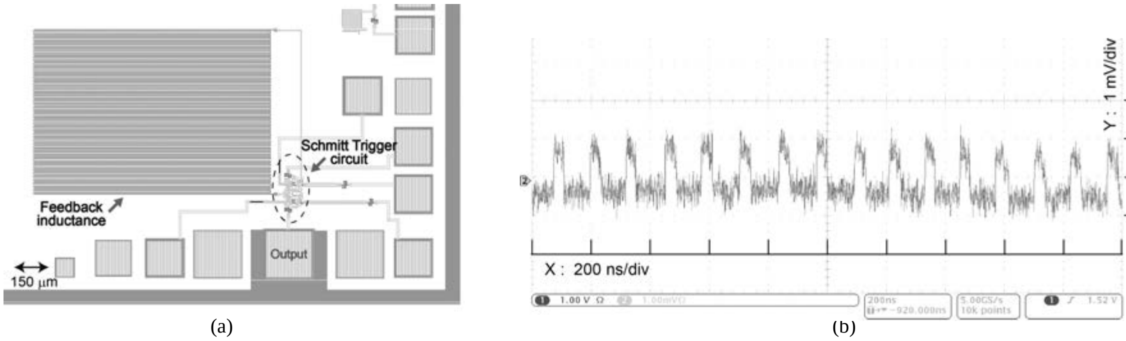


Fig. 4. (a) Design layout of the fabricated oscillator. (b) Experimental test result of the fabricated oscillator. The output voltage is amplified using an AC-coupled 50 Ω broadband amplifier with a gain of 21 dB.

4. Conclusion

An experimental demonstration and performance estimation of a new superconducting relaxation oscillator using the Schmitt trigger inverter were reported. The relaxation oscillator was designed using a coupled SQUIDs threshold gate, and its operation was confirmed numerically. The oscillation frequency can be easily changed by changing the additional integrating circuit. A high-speed operation of the relaxation oscillator up to a frequency of 6.5 GHz was confirmed numerically. The designed relaxation oscillator using the Schmitt trigger inverter circuit was fabricated using the 2.5kA/cm^2 Nb/AlOx/Nb process and further tested. In addition, the operation of the fabricated relaxation oscillator was experimentally demonstrated.

Acknowledgements

The circuits were fabricated in the clean room for analog-digital superconductivity (CRAVITY) of National Institute of Advanced Industrial Science and Technology (AIST) with the standard process 2 (STP2).

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